Bottom Interaction in Ocean Acoustic Propagation

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LONG-TERM GOALS

The long term objective is to understand the dominant physical mechanisms responsible for propagation and scattering over distances from tens to thousands of kilometers in the deep ocean where the sound channel is not bottom limited. The specific goal is to study the role of bottom interaction and bathymetry on the stability, statistics, spatial distribution and predictability of broadband acoustic signals observed just above and on the deep seafloor (greater than the critical depth). What is the relationship between the seismic (ground motion) noise on the seafloor and the acoustic noise in the water column? What governs the trade-offs in contributions from local and distant storms and in contributions from local and distant shipping? How effective is seafloor bathymetry at stripping distant shipping noise from the ambient noise field?

This project addresses "the effects of environmental variability induced by ocean internal waves, internal tides and mesoscale processes, and by bathymetric features including seamounts and ridges, on the stability, statistics, spatial distribution and predictability of broadband acoustic signals..." (quote from the Ocean Acoustics web page). Understanding long range acoustic propagation in the ocean is essential for a broad range of Navy applications such as the acoustic detection of ships and submarines at long ranges, avoiding detection of ships and submarines, long range command and communications to submerged assets, and improving understanding of the environment through which the Navy operates.

OBJECTIVES

During the 2004 Long-range Ocean Acoustic Propagation Experiment (LOAPEX) (Mercer *et al.*, 2009) a new class of acoustic arrivals was observed on ocean bottom seismometers (OBSs) for ranges from 500 to 3200km (Stephen *et al.*, 2009). The arrivals were called Deep Seafloor Arrivals (DSFAs), because they were the dominant arrivals on the ocean bottom seismometers (OBSs), but were very weak on the deep vertical line array (Deep VLA), located above 750 m from the seafloor. Stephen et al (2013) attributed some of these arrivals to bottom-diffracted, surface-reflected (BDSR) energy that scattered from a seamount near the Deep VLA and subsequently reflected from the sea surface before arriving at the OBSs. BDSR arrivals are a palimpsest in the propagated ocean acoustic field. They are barely observable when the ambient noise and PE predicted arrivals are loud (such as in the sound

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channel), but become the dominant arrivals when the ambient noise and PE predicted arrivals are quiet (such as on the deep seafloor).

Since NPAL04 we have carried out two experiments specifically aimed at studying DSFAs and BDSRs. The first experiment (OBSAPS - Ocean Bottom Seismometer Augmentation in the Philippine Sea) was carried out in April-May 2011 near the location of the PhilSea10 Distributed Vertical Line Array (DVLA) (Stephen *et al.*, 2011). The second experiment (OBSANP - Ocean Bottom Seismometer Augmentation in the North Pacific) was carried out in June-July 2013 near the location of the NPAL04 Deep Vertical Line Array (Stephen *et al.*, in press). Both experiments quantitatively compared the signal and noise levels in the 50-400Hz band on the hydrophones and geophones at the seafloor to the hydrophones suspended up to 1 kilometer above the seafloor, for ranges from near zero to 250km. We also acquired seafloor ambient noise at the sites in the band from 0.03 - 80Hz that can be compared to other deep-water sites in the Pacific Ocean.

The objective of these grants is to analyze the data from the two experiments and to disseminate the results. Specific questions to be addressed include: i) Is there evidence for Deep Seafloor Arrivals on OBSAPS and OBSANP that are similar to the ones observed on NPAL04? ii) What is the frequency dependence of the deep arrival structure from 50 - 400Hz? iii) What is the range dependence of the deep arrival structure out to 250km? iv) What is the azimuth dependence of the deep arrival structure? v) What are the relative SNRs of arrivals on vertical and horizontal geophones, co-located seafloor hydrophones and moored hydrophones (from 20m to 1000m off the bottom)? vi) What are the phase relationships between pressure and vertical and horizontal particle motion for deep seafloor arrivals and ambient noise? vii) What is the relationship between the observed deep arrival structure and the PE predicted arrival structure?

APPROACH

Three types of figures form the basis for the data reduction and analysis:

1) Time series of the time compressed traces as a function of range (for the 50km radials and the one 250km long line), as a function of azimuth (for the Star of David pattern) and as a function of time (for the station stops). For the 50km radials and Star of David we transmitted M-sequences at 77.5, 155 and 310Hz; for the 250km long-range tow we transmitted one M-sequence at 77.5Hz; and for the station stops we transmitted M-sequences at 77.5, 102.3, 155, 204.6 and 310Hz.

2) SNR summaries, similar to Figure 26 of the OBSAPS cruise report (Stephen *et al.*, 2011), are an excellent way to reduce intensive data sets (we transmitted for 11.5days and 15days on OBSAPS and OSNANP, respectively) into a few meaningful parameters.

3) Spectrograms for all receivers for the whole recording period show the variability with time and frequency of the ambient noise field. On OBSAPS we recorded during the typhoon on JD130/2011 and on OBSANP we recorded during an extremely quite period on JD171-172/2013 so we have samples of calm and rough conditions.

After the data reduction the first step is to identify as many instances of DSFAs on the 77.5Hz transmissions as possible and to describe their characteristics. How do they appear across the various receivers (DVLA and OBSs)? How do they appear on the various sensors on the same OBS (vertical

geophone, horizontal geophones, hydrophones)? How is their appearance affected by background noise levels? Where are the diffraction points located and do they correspond to particular seafloor features? Is the occurrence of DSFAs the same at all of the transmitted frequencies (77.5, 155, 310Hz)?

WORK COMPLETED

We have scanned all of the time-compressed data for the radial lines on OBSAPS and we have identified four seafloor diffractors (Figure 1). Three of these (A-C) correspond to small seamounts on the seafloor. Diffractor D however does not correspond to any obvious seafloor feature. As an example, the BDSR arrival from diffractor D appears for transmissions on the Southwest line at ranges from 10 to 30km (Figure 2). The BDSR arrival is most clear on the vertical component geophone on the West OBS, is weak on the North OBS, is very weak on the South OBS and is undetectable on the DVLA hydrophone module 12m above the seafloor (Figure 3). Oddly, even among the co-located sensors on the West OBS the BDSR arrival is loud on the vertical component (louder than the direct arrival at 25.8km range), quite weak on the hydrophone module, and undetectable on the horizontal components (Figure 4). Furthermore BDSR arrivals from Diffractor D seem to be significantly excited by transmissions only on the Southwest radial.

RESULTS

The results of last year's (2013) work appeared primarily in the Special Issue of JASA on Deep Water Ocean Acoustics that was published in October 2013. Stephen et al (2013) report on the analysis of the NPAL04 data that identifies the BDSR path. Preliminary results from the OBSAPS experiment are presented in Worcester et al (2013). The geological background on the Philippine Sea and our proposed acoustic model is described in Heaney et al (2013). We also worked with Simon Freeman on his analysis of T-phases in the Philippine Sea (Freeman *et al.*, 2013).

Preliminary results from the OBSAPS experiment were presented at the 2014 ONR Acoustics Peer Review meeting (Stephen *et al.*, 2014) and further work will be presented at the PhilSea Data Analysis Workshop in October 2014. A cruise report for the OBSANP experiment is in press (Stephen *et al.*, in press).

IMPACT/APPLICATIONS

Leakage of energy into DSFAs will have at least three consequences. First, if energy leaks out of the waveguide in a systematic fashion, it will increase transmission loss for known modes in the waveguide. These will be scattering losses as opposed to intrinsic attenuation. If the leaked energy re-emerges down range (as BDSR multipath arrivals), perhaps only to near-seafloor receivers, there will be less overall transmission loss (more signal). In this case interpretations may require new types of modes. Second, leakage into DSFAa will result in long-range detections and observations on non-traditional sensors such as deep boreholes in the seafloor in water depths well-below the critical depth (Araki *et al.*, 2004). Third, the physics of short and long-range sound propagation that we are observing in the controlled-source transmissions also applies to local and distant shipping noise. For example, the DSFAs observed on NPAL04 provided a mechanism for taking long-range energy from 4250m depth into the deep shadow zone at 5000m depth. So the presence of DSFAs on various sensors requires a re-evaluation of the signal and noise energy budgets.

TRANSITIONS

Transitions to 32ASW project "Behavior of very low frequency near bottom ambient noise in deep water".

RELATED PROJECTS

LOAPEX - ONR Award Number N00014-1403-1-0181

SPICEX - ONR Award Number N00014-03-1-0182

PhilSea09 and PhilSea10 - ONR Award Number N00014-08-1-0840

OBSAPS - ONR Award Number N00014-10-10994 and N00014-10-1-0990.

OBSANP - ONR Award Number N00014-10-10987 and N00014-12-M-0394

REFERENCES

Araki, E., Stephen, R. A., Shinohara, M., Kanazawa, T., and Suyehiro, K. (**2004**), T-phase observed at deep seafloor boreholes, in *Proceedings, Seismo-Acoustic Applications in Marine Geology and Geophysics Workshop, Woods Hole Oceanographic Institution, 24-26 March 2004*, edited by Odom, R. I. and Stephen, R. A., (Applied Physics Laboratory, University of Washington, Seattle, WA).

Freeman, S. E., D'Spain, G. L., Lynch, S. D., Stephen, R. A., Heaney, K. D., Murray, J. J., Baggeroer, A. B., Worcester, P. F., Dzieciuch, M. A., and Mercer, J. A. (**2013**). "Estimating the horizontal and vertical direction-of-arrival of water-borne seismic signals in the northern Philippine Sea," J. Acoust. Soc. Am. **134**, 3282-3298.

Heaney, K. D., Campbell, R. L., Murray, J. J., Baggeroer, A. B., Scheer, E. K., Stephen, R. A., D'Spain, G. L., and Mercer, J. A. (**2013**). "Deep water towed array measurements at close range," J. Acoust. Soc. Am. **134**, 3230-3241.

Mercer, J. A., Colosi, J. A., Howe, B. M., Dzieciuch, M. A., Stephen, R., and Worcester, P. F. (**2009**). "LOAPEX: The long-range ocean acoustic propagation experiment," IEEE J. Ocean. Eng. **34**, 1-11.

Stephen, R. A., Bolmer, S. T., Dzieciuch, M. A., Worcester, P. F., Andrew, R. K., Buck, L. J., Mercer, J. A., Colosi, J. A., and Howe, B. M. (**2009**). "Deep seafloor arrivals: An unexplained set of arrivals in long-range ocean acoustic propagation," J. Acoust. Soc. Am. **126**, 599-606. 10.1121/1.3158826.

Stephen, R. A., Bolmer, S. T., Udovydchenkov, I. A., Dzieciuch, M. A., Worcester, P. F., Andrew, R. K., Mercer, J. A., Colosi, J. A., and Howe, B. M. (**2013**). "Deep seafloor arrivals in long range ocean acoustic propagation," J. Acoust. Soc. Am. **134**, 3307-3317. 10.1121/1.4818845.

Stephen, R. A., Bolmer, S. T., Worcester, P. F., and Dzieciuch, M. A. (2014), Bottom interaction acoustics in the Philippine Sea, paper presented at ONR Acoustics Peer Review Meeting, Stennis Space Center, MS.

Stephen, R. A., Kemp, J., McPeak, S. P., Bolmer, S. T., Carey, S., Aaron, E., Campbell, R., Moskovitz, B., Calderwood, J., Cohen, B., Worcester, P. F., and Dzieciuch, M. A. (**2011**), Ocean Bottom

Seismometer Augmentation of the Philippine Sea Experiment (OBSAPS) Cruise Report, WHOI Technical Report 2011-04, (Woods Hole Oceanographic Institution, Woods Hole, MA).

Stephen, R. A., Udovydchenkov, I. A., Worcester, P. F., Aaron, E., Bolmer, S. T., Carey, S., McPeak, S. P., Swift, S. A., and Dzieciuch, M. A. (**in press**), Ocean Bottom Seismometer Augmentation in the North Pacific (OBSANP) - Cruise Report, (Woods Hole Oceanographic Institution, Woods Hole, MA).

Worcester, P. F., Dzieciuch, M. A., Mercer, J. A., Andrew, R. K., Dushaw, B. D., Baggeroer, A. B., Heaney, K. D., D'Spain, G. L., Colosi, J. A., Stephen, R. A., Kemp, J. N., Howe, B. M., Van Uffelen, L. J., and Wage, K. E. (**2013**). "The North Pacific Acoustic Laboratory (NPAL) deep-water acoustic propagation experiments in the Philippine Sea," J. Acoust. Soc. Am. **134**, 3359-3375. DOI: 10.1121/1.4818887.

PUBLICATIONS

Stephen, R.A., Bolmer, S.T., Udovydchenkov, I.A., Worcester, P.F., Dzieciuch, M.A., Andrew, R.K. , Mercer, J.A., Colosi, J.A., and Howe, B.M., 2013. Deep seafloor arrivals in long range ocean acoustic propagation. J. acoust. Soc. Am., 134, 3307-3317. [published, refereed]

Stephen, R.A., Udovydchenkov, I.A., Worcester, P.F., Aaron, E., Bolmer, S.T., Carey, S., McPeak, S.P., Swift, S.A. and Dzieciuch, M.A., in press. Ocean bottom seismometer augmentation in the North Pacific (OBSANP) - Cruise Report. WHOI Technical Report, Woods Hole Oceanographic Institution, Woods Hole, MA, WHOI-2014-06. [in press]

Freeman, S.E., D'Spain, G.L., Lynch, S.D., Stephen, R.A., Heaney, K.D., Murray, J.J., Baggeroer, A.B., Worcester, P.F., Dzieciuch, M.A., and Mercer, J.A., 2013. Estimating the horizontal and vertical direction-of-arrival of water-borne seismic signals in the northern Philippine Sea. J. acoust. Soc. Am., 134, 3282-3298. [published, refereed]

Heaney, K.D., Campbell, R.L., Murray, J.J., Baggeroer, A.B., Scheer, E.K., Stephen, R.A., D'Spain, G.L. and Mercer, J.A., 2013. Deep water towed array measurements at close range. J. acoust. Soc. Am., 134, 3230-3241. [published, refereed]

McPeak, S.P., D'Spain, G.L. and Stephen, R.A., 2013 OBSANP data acquisition system: Operator's manual and system overview. WHOI Technical Report, Woods Hole Oceanographic Institution, Woods Hole, MA. WHOI-2013-06. [published]

Worcester, P.F., Dzieciuch, M.A., Mercer, J.A., Andrew, R.K., Dushaw, B.D., Baggeroer, A.B., Heaney, K.D., D'Spain, G.L., Colosi, J.A., Stephen, R.A., Kemp, J.N., Howe, B.M., Van Uffelen, L.J. and Wage, K.E., 2013. The North Pacific Acoustic Laboratory deep-water acoustic propagation experiments in the Philippine Sea, J. acoust. Soc. Am., 134, 3359-3375. [published, refereed]

Worcester, P.F. and Stephen. R.A., 2013. Ocean bottom seismometer augmentation in the North Pacific (OBSANP): Cruise quick-look report. Scripps Institution of Oceanography. La Jolla, CA. [published]

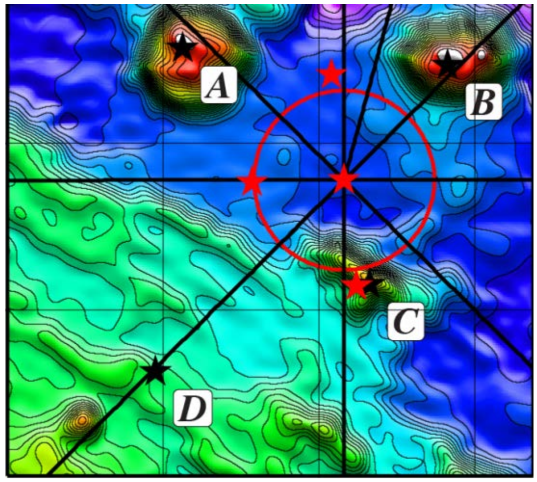

Figure 1: Receivers (red stars) and potential seafloor diffractors (black stars, labelled A-D) are overlain on the bathymetry for the OBSAPS experiment in the Philippine Sea. The red circle is 2km from the O-DVLA (middle red star). The red stars North, West and South of the O-DVLA are OBSs. Diffractors A, B, and C are on small seamounts. Diffractor D does not correspond to any obvious seafloor relief. The acoustic source was towed along the black lines at ranges out to 50km. The O-DVLA is in 5433m water depth and the tops of Seamounts A and B are at ~4900m. [Ralph_Box.jpg]

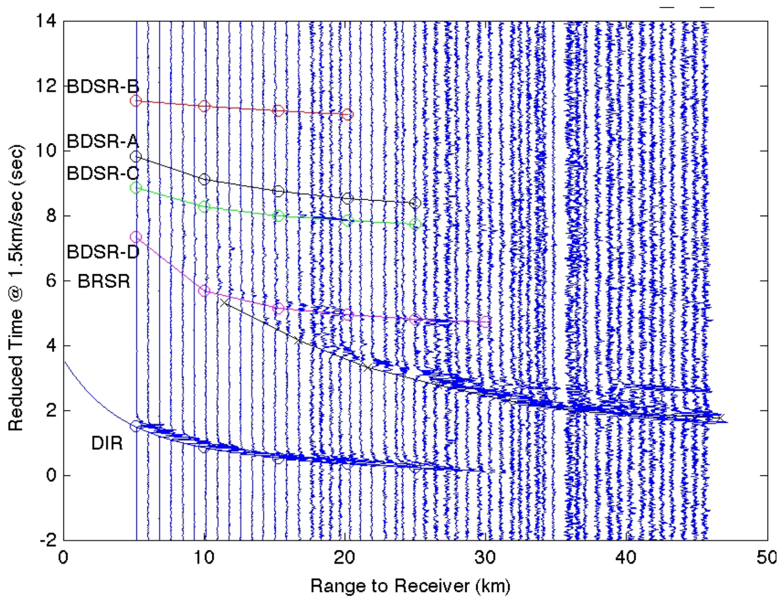

Figure 2: Record section of vertical component traces (after time compression) on the West OBS for transmissions on the radial line to the Southwest of the O-DVLA (see Figure 1). The direct energy (DIR, blue line with circles) is the largest arrival at short ranges but fades beyond 28km or so due to refraction in the sound speed profile. The bottom-reflected surface-reflected energy (BRSR - black line with x's) is the largest arrival beyond 28km or so. Travel-time curves for the four bottom-diffracted surface-reflected arrivals are computed based on the locations of the diffractors in Figure 1. Arrivals corresponding to diffractor D (BDSR_D - magenta line with circles) appear between 10 and 28km. Arrivals corresponding to diffractor C (BDSR_C - green line with circles) appear between 18 and 20km. In this case there are no arrivals corresponding to diffractors A (black line with circles) and B (red line with circles). [PhilSea_RT_14_SW_5a_OBS_W__3.jpg]

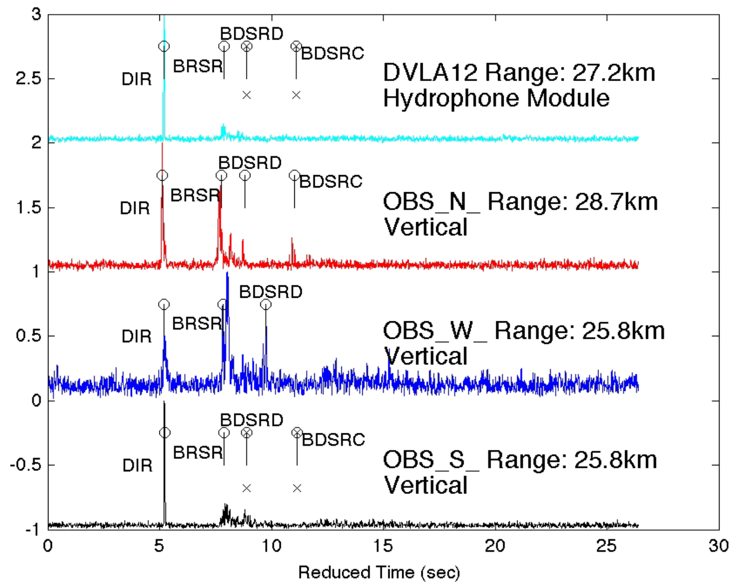

Figure 3: Traces for the four receivers (vertical components on the three OBSs and the bottom hydrophone module on the O-DVLA) for a transmission at 27.2km southwest of the O-DVLA show the direct (DIR), the bottom-reflected surface-reflected (BRSR) and two bottom-diffracted surface reflected arrivals from points C and D (BDSRC and BDSRD). The BDSR arrival from diffractor D is strong on the West OBS, is weak on the North and South OBSs and is essentially undetectable at the bottom of the O-DVLA. The BDSR arrival from diffractor C is only detectable on the North OBS. Traces have been shifted in time to align the DIR arrivals. [PhilSea_RT_14_6a_abs_2.jpg]

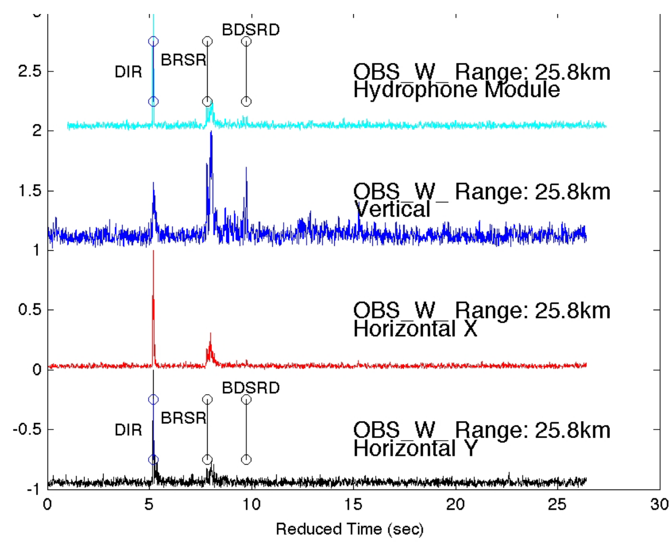

Figure 4: Four channels on the West OBS for a transmission 27.2km southwest of the O-DVLA. The differences in these co-located traces (all sensors are on the same OBS) are remarkable. The bottom-diffracted surface-reflected arrival from 'D' is best seen on the vertical geophone and is only weakly observed on the co-located hydrophone module. This is consistent with the whole OBSAPS data set. BDSR arrivals are dominant on vertical component geophones and very weak on hydrophone modules either in the O-DVLA or co-located on the OBSs. [PhilSea_RT_14_6b_2.jpg]